Canopy Temperature of Irrigated Winter Wheat

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ABSTRACT

THE canopy temperature of four winter wheat varieties—TAM-105, TAM-108, Sturdy, and Scout—was studied under four irrigation regimes. Non-water-stressed baselines for the crop stress index (CWSI) were developed for the individual varieties and for both pre-and post-heading phenology using three data smoothing techniques. Non-transpiring (stressed) baselines were developed from the unstressed baselines and compared to canopy-air temperature differentials that were measured in water-stressed plots. Wind speed did not affect the non-transpiring baselines in the high windspeeds common to the Southern Great Plains.

Aerodynamic and canopy diffusion resistances were predicted using the baseline relationships and energy balance theory. The predicted aerodynamic resistance was similar between pre- and post-heading phenology and between the values predicted from the non-transpiring and non-water-stressed baselines. The predicted canopy resistance increased from pre- to post-heading.

The CWSI was related to midday leaf water potential (LWP) of winter wheat, but the relationship depended on phenology. The phenology response in LWP may be due to differences in water relations between winter wheat flag leaves and canopy leaves. The CWSI was useful for evaluating crop water stress in winter wheat in this region and should be useful for timing of spring irrigations for winter wheat.

INTRODUCTION

Winter wheat is a major crop produced in the Southern Great Plains of the United States. It is produced under both dryland and irrigated cultures and is an important winter forage crop for livestock grazing in this region. This region covers parts of four states—High Plains of Texas, Panhandle of Oklahoma, and parts of eastern New Mexico and southwestern Kansas. The irrigated areas in this region use primarily groundwater taken from the Ogallala aquifer. Irrigated winter wheat is grown on approximately 600,000 ha of land, and limited irrigation (irrigation where the full water demands of the crop are only partially met) is being practiced on an increasing portion of this area. Depleting groundwater, increasing energy costs for pumping, and low crop process are largely responsible for the decreased use of irrigation water on winter wheat in this region. Recently, Musick et al. (1984) summarized much of the information on irrigation water management of winter wheat on the High Plains of Texas. One dramatic improvement has been the development of higher yielding, shorter stature winter wheat varieties, which markedly improve the water use efficiency (WUE) (yield per unit of evapotranspired water) of irrigated winter wheat in this region. Musick et al. (1984), proposed that this dramatic increase in WUE of irrigated winter wheat will continue to make winter wheat a major irrigated crop in this region and the use of limited irrigation on winter wheat will continue to expand.

Criteria for timing limited irrigation applications to winter wheat may require the use of plant-based measurements to detect the crop stress levels as opposed to more traditional methods of irrigation timing such as soil moisture measurements, soil water balance models, or calendar schedules. Jackson (1982) reviewed the use of infrared thermometry to detect crop temperatures and its utility for inferring crop water stress from canopy temperature and other environmental measurements.

Ehrler et al. (1978) demonstrated that the difference in leaf to air temperature (measured above the crop) of wheat was related to the atmospheric vapor pressure deficit (VPD). Idso et al. (1981a) confirmed this observation for alfalfa at several locations and associated microenvironments. They proposed that this relationship normalized the crop canopy-air temperature differential (T_c - T_a) for the environmental interactions and developed a crop water stress index (CWSI) to quantify the crop water stress. Idso (1982) further defined "non-water-stressed baselines" for 26 different species for clear sky conditions and found that these baselines were different for various phenological stages in certain crops. Jackson et al. (1981) provided a theoretical formulation for the CWSI. Several proposals have been made to utilize the CWSI and/or canopy temperature to determine the timing of irrigations (Reginato, 1983; Howell et al., 1984; Geiser et al., 1982).

The purpose of this article is to determine the relationship between canopy temperature and associated environmental parameters for irrigated winter wheat in the semi-arid environment of the Southern Great Plains.

Article was submitted for publication in June, 1986; reviewed and approved for publication by the Soil and Water Div. of ASAE in December, 1986. Presented as ASAE paper No. 85-2615.

Contribution from USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX.

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Acknowledgements: The authors gratefully acknowledge the assistance of D. A. Dusek, Agronomist, USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX, for conduct of the experiment; K. S. Copeland, Biological Technician, USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX,for data processing and analysis; and A. C. Mathers, Soil Scientist (retired), USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX, for collection and processing of the leaf water potential measurements.

THEORY AND RELATED RESEARCH

The energy balance of a crop surface was expressed by Monteith (1973) as the following:

$$R_n + G + H + LE = 0 \quad \ldots [1]$$

where R_n is the net radiation flux, G is soil heat flux, H is the sensible heat flux, L is the latent heat of vaporization (J kg^{-1}), and E is the evaporation flux (kg m^{-2} s^{-1}) with all energy terms in units of W m^{-2} and with all terms defined as positive towards the plant surface. The sensible heat flux can be defined as follows:

$$H = -\rho\, C_p\, (T_c - T_a)\, (r_a)^{-1} \quad \ldots [2]$$

where ρ is air density (kg m^{-3}), C_p is specific heat of air at constant pressure (J $C^{-1}kg^{-1}$), and r_a is the canopy aerodynamic resistance (s m^{-1}). The latent heat flux can be defined as follows:

$$LE = -\rho\, C_p\, (e_c^* - e_a)\, [\gamma\, (r_a + r_c)]^{-1} \quad \ldots [3]$$

where e^*_c is saturated vapor pressure (kPa) at T_c. e_a is the ambient vapor pressure (kPa), γ is the psychrometric constant (kPa C^{-1}) defined as [P C_p $L^{-1}\varepsilon^{-1}$, where P is barometric pressure (kPa) and ε is the ratio of mole weights of water and air (0.622)], and r_c is the canopy diffusion resistance (s m^{-1}). Jackson et al. (1981) presented the following relationship for the canopy-air temperature differential:

$$T_c - T_a = \frac{r_a R_n}{\rho C_p} \left(\frac{\gamma (1 + r_c/r_a)}{[\Delta + \gamma\, (1 + r_c/r_a)]} \right) - \left(\frac{(e_a^* - e_a)}{[\Delta + \gamma\, (1 + r_c/r_a)]} \right) \quad \ldots [4]$$

where Δ is the slope of the saturated vapor pressure curve (kPa C^{-1}) and e^*_a is the saturated vapor pressure at the ambient air temperature (kPa) [note: ($e^*_a - e_a$) =VPD]. Equation [4] was shown by Idso (1983) and O'Toole and Real (1986) to be compatible with the empirically determined "non-water-stressed baselines" expressed in the form

$$T_c - T_a = a - b\ VPD \quad \ldots [5]$$

where a (C) and b (C kPa^{-1}) are linear regression coefficients (intercept and slope, respectively). O'Toole and Real (1986) determined that linear relationships as described by equation [5] should be the best approximation to different theoretical estimates (constant R_n, r_a, and r_c). The theoretical estimates are actually concave facing upward when determined with e_a held constant while varying T_a and are concave facing downward when determined with T_a held constant while varying e_a. Also, procedures used to estimate Δ can affect the theoretical estimates. Jackson et al. (1981) proposed that Δ be estimated at the mean temperature between T_c and T_a, while Idso (1983) proposed Δ be estimated as ($e^*_c - e^*_a$) ($T_c - T_a$)$^{-1}$.

As presented in equation [4], the canopy-air temperature differential exhibits a complex relationship to many parameters—net radiation, air temperature, ambient vapor pressure, barometric pressure, windspeed, atmospheric stability, and the many crop specific factors that determine r_c. Yet in some environments, the canopy-air temperature differential relationship seems to be related simply to VPD (for example, see Idso, 1982; Howell et al., 1984) while in other environments the relationship seems to be more complex depending on several parameters (for example, see Geiser et al.,1982; Hipps et al., 1985).

The crop water stress index (CWSI) as first presented empirically by Idso et al. (1981a) consists of two lines—a lower baseline representing a non-water-stressed crop and an upper baseline representing a non-transpiring (water stressed) crop. Jackson et al. (1981) showed similar theoretical results and proposed

$$CWSI = 1 - E/E_p \quad \ldots [6]$$

where E_p is the "potential" evapotranspiration from a non-water-stressed crop. Fig. 1 presents a diagrammatic representation of the CWSI for winter wheat showing two sets of upper and lower baselines—one set for the pre-heading and one set for the post-heading growth stages. The CSWI has been defined simply as

$$CWSI = [(T_c - T_a) - LL]\ (UL - LL)^{-1} \quad \ldots [7]$$

where UL represents the non-transpiring upper baseline and LL represents the non-water-stressed lower baseline, with both UL and LL being determined at the particular T_a and VPD. Idso et al. (1981a) proposed that the non-transpiring upper baseline would not depend on VPD and presented the following method for estimating T_c - T_a for non-transpiring crops:

$$T_c - T_a = a - b\ VPG \quad \ldots [8]$$

where a and b are determined by the non-water-stressed lower baseline equation [5] and VPG is the negative atmospheric vapor pressure gradient necessary for zero canopy-air vapor pressure gradient [VPG = $e^*(T_a)$ - $e^*(T_a + a)$, where e* represents saturated vapor pressure at the associated temperature]. Thus, using this procedure, UL will depend only on T_a. The theoretical

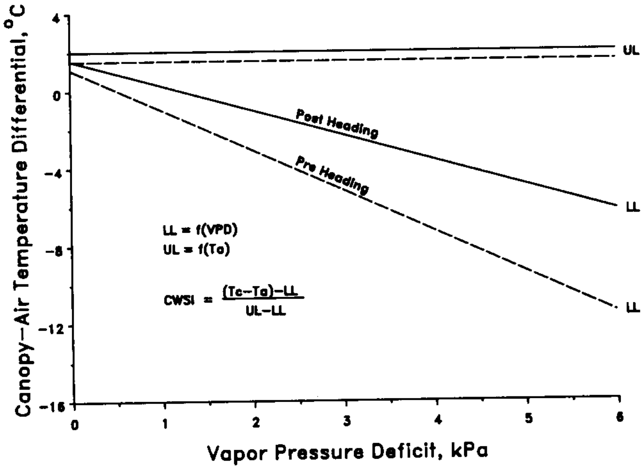

Fig. 1—Representation of the crop water stress index for winter wheat illustrating the upper non-transpiring baselines and the lower non-water-stressed baselines for pre- and post-heading conditions.

estimate of the non-transpiring upper baseline can be determined by assuming that the latent heat flux and soil heat flux are zero and combining equation [1] with equation [2] for the following result:

$$T_c - T_a = r_a R_n (\rho C_p)^{-1} \quad \text{[9]}$$

Equation [9] predicts a positive UL in agreement with most of the empirical findings. O'Toole and Hatfield (1983) determined that the UL procedure of Idso et al. (1981a) should also depend on windspeed as predicted by equation [9], since r_a should be inversely related to windspeed. Hipps et al. (1985) also discuss theoretical developments that lead to utilization of other environmental parameters, particularly net radiation and windspeed, in the interpretation and development of the baselines for the CWSI.

MATERIALS AND METHODS

Winter wheat (*Triticum aestivum L.*) was planted on fallowed, level basins at the USDA-ARS, Conservation and Production Research Laboratory (35° N. Lat., 102° W. Long., 1,170 m elevation) near Bushland, TX, on September 28, 1983, in 0.25-m spaced E-W rows, at a seeding rate of 7 g m^{-2}, using a grain drill. The soil at this site is classified as Pullman Clay loam (Torrertic Paleustoll) and is characterized by a 1.0- to 1.5-m clay profile overlaying a caliche layer (about 50% calcium carbonate). Preplant application of N at the rate of 8 g m^{-2} and a 150 mm preplant irrigation was applied uniformly to the plots, and all other cultural operations for weed and pest control were applied uniformly. The basins were 9.8 m in width and 32 m in length, flat planted, and irrigated by gated-pipe with the irrigation water accurately metered to each plot with an in-line propeller-type water meter.

Four winter wheat varieties—Sturdy, Scout, TAM-105, and TAM-108—were studied along with four irrigation treatments—no spring irrigation (T-1), one spring irrigation (T-2), two spring irrigations (T-3), and four spring irrigations (T-4). All spring irrigations were 100 mm, and the treatments were applied serially such that all irrigation treatments were irrigated at the first irrigation date except the non-irrigated treatment, all remaining irrigation treatments were irrigated at the second irrigation date except the non-irrigated and one-irrigation treatments, etc. The dates of irrigations were March 22 (DOY 82) at tillering, April 26 (DOY 117) at jointing, May 16 (DOY 137) at heading, and June 1 (DOY 153) at grain filling. In all cases, irrigation water remained ponded on the plots for at least 2 days following application. The experimental design was a complete randomized block with three replications.

Canopy temperature was measured with an Everest* model 110 infrared thermometer (IRT) with a narrow field of view (about 3 deg solid angle between half-intensity rays) equipped with a 8 to 14 μ spectral band-pass filter. The IRT was operated with the emissivity adjustment set at 0.98. The IRT was compared frequently to an Everest black-body standard to check instrument performance. The canopy temperature was recorded from the IRT as an analog signal by an Omnidata polycorder model 516 as an average of five instantaneous readings taken from an oblique view angle to the crop rows at an IRT view angle about 60 to 70 deg from nadir. These angles minimized any views of soil and sky background so that the IRT viewed primarily the canopy surface. IRT measurements were recorded from both the east and west side of each plot. Wet- and dry-bulb ambient temperature measurements were made with two Environmental Technics Corp. model Psychro-Dyne psychrometers at the north and south ends of the plot area about 1 m above the crop and were hand entered into the polycorder at 5 min increments during the measurement sequence. The data from the polycorder were decoded and transmitted to a microcomputer for preprocessing and later transferred for final analysis to a minicomputer. The mean air temperature was determined from the average of the dry-bulb temperature readings during the measurement period. The mean VPD was computed as the average of the computed instantaneous VPDs using the corresponding instantaneous wet- and dry-bulb temperatures and the standard psychrometer equation (List, 1971) during the measurement period. The VPD computations used a mean barometric pressure of 89 kPa for the Bushland location.

Micrometeorological parameters of solar radiation, air temperature, relative humidity, and windspeed were recorded at the north and south ends of the plots with a Campbell Scientific Inc. model CR-7 data acquisition system. Solar radiation was measured with Li-Cor Inc. model LI-200SB silicon-cell pyranometers, and air temperature was measured with naturally-aspirated, radiation-shielded copper-constantan thermocouples. Relative humidity was measured with a hair element humidity sensor and linear variable differential transformer within the air temperature housing (Duke and Blue, 1985) which was mounted at 2-m elevation above the ground. Windspeed was measured at 2 m above the ground with Belfort model 5-349 cup anemometers by counting switch closures for each 161 m of windrun. The CR-7 averaged or totalized each parameter for 30-min time periods and recorded the data on cassette tapes, which were later decoded and transmitted to a microcomputer for processing.

Leaf water potential was determined by the psychrometric method using J.R.D. Merrill Specialty Equipment model 76-13C leaf cutter psychrometers which were measured with a Merrill model 82-22 psychrometer meter. In situ samples (three per plot) of 5-mm diameter leaf discs were taken from fully expanded, exposed, and sunlit leaves (normally the upper leaf or flag leaf) at solar noon, and the samples were sealed into the psychrometer chamber and returned to the laboratory. The samples were then placed into an insulated water bath maintained at 30 ± 0.1°C by a Tecam model TU-15 temperature controller and allowed to equilibrate for 3 h. The individual samples were then measured using the psychrometric method with a 5 mA cooling current applied for 15 s and a 5-s delay in the reading. The measurements were manually recorded and entered into a microcomputer for statistical analysis.

Soil water contents were measured periodically in each plot to a depth of 1.6 m with 0.2-m increments with a Troxler model 3221 neutron depth moisture gauge. The

*Mention of a trade name or product does not constitute or imply an endorsement for use by the USDA-ARS, but is intended solely as information for the reader.

neutron probe was field calibrated at a nearby site. The profile water content was determined by integrating the soil water content measurements over the profile depth. A soil water balance model described in Howell and Musick (1985) was used to estimate the daily profile soil water contents in each irrigation treatment.

RESULTS AND DISCUSSION

Six sets of diurnal IRT measurements (normally from 0830 to 1530 CST) were obtained at hourly intervals under mostly clear sky conditions. The dates of measurements were April 23 (DOY 114), May 3 (DOY 124), May 10 (DOY 131), May 21 (DOY 142), May 31 (DOY 152), and June 4 (DOY 156). The date of heading was May 15, which separated pre- and post-heading data analyses. The measurements taken on May 3 (DOY 124) and May 21 (DOY 142) from the irrigated treatment (T-4) were analyzed as "non-water-stressed" since irrigations had been applied to them on April 26 and May 16, respectively. Rainfall amounts of 26 mm and 1 mm on April 29 and May 19, respectively, were received following the irrigations but before the two "non-water-stressed" baselines were determined; and the profile soil water contents were greater than 90% of the available soil water. Monthly rainfall totals for the 1984 spring and summer growing season totaled 4 mm for February, 26 mm for March, 37 mm for April, 1 mm for May, 121 mm for June, and 70 mm for July. Fig. 2 shows the seasonal soil water profiles estimated for each irrigation

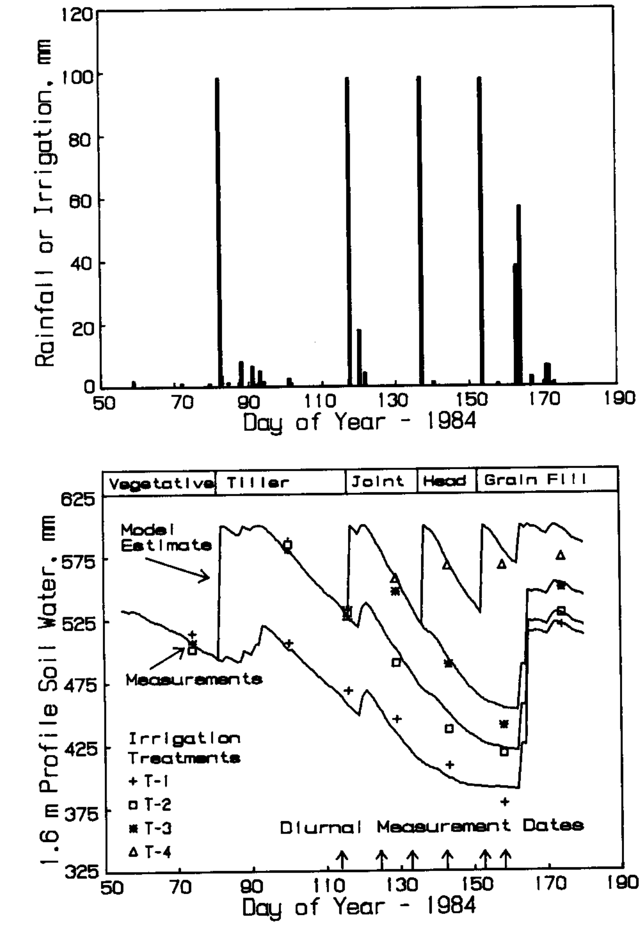

Fig. 2—Rainfall, irrigation, and profile soil water contents during the experiment.

treatment, along with the rainfall and irrigation amounts. The T-4 treatment was irrigated when approximately 50% of the available water was extracted. Fig. 2 illustrates that on the measurement dates, the T-1 treatment had less than 25% available profile soil water but that transpiration was still significant until about heading (May 15, DOY 136).

Table 1 presents a summary of the linear regression results for the pre- and post-heading "non-water-stressed" baselines. The data were analyzed with three smoothing techniques—plot mean (mean of 10 readings from two directions), treatment mean (mean of 30 readings from three replications), and treatment mean smoothed with a 3-h equally-weighted running mean. The 3-h equally-weighted running mean was used by Idso (1982) to determine the "non-water-stressed" baselines for 26 species. All the linear regressions were significant at 0.01 level as determined by an analysis of variance. The linear regressions within each smoothing technique were tested for variety commonality (Freese, 1980). The linear regressions for the different varieties were not significantly different (0.05 level) on May 3 and on May 21 for the plot mean and the treatment mean data smoothing techniques but were significantly different (0.05 level) for the 3-h running mean smoothing technique. Blum et al. (1982) proposed that canopy temperature was genetically controlled and that similar procedures could be used to screen wheat varieties for drought avoidance. The coefficient of determinations ranged from 0.751 to 0.988 and increased 10% from the plot mean smoothing technique to the treatment mean smoothing technique and increased an additional 4% in the 3-h running mean smoothing technique. The mean standard error of the estimate of y on x decreased from 0.436 to 0.267 and to 0.102°C for the plot mean, treatment mean, and 3-h running mean smoothing techniques, respectively. The three smoothing techniques were not statistically different (0.05 level). Figs. 3 and 4 show the 3-h smoothed linear regressions for the pre- and post-heading conditions, respectively, for TAM-105. The baselines determined for spring wheat (Produra) at Phoenix and statistically different (0.05 level). There was not a significant difference (0.05 level) in "non-water-stressed" baselines for the T-4 treatment after heading on the May 21 (DOY 132) and the May 31 (DOY 152) measurement dates. The separation in baselines for pre-and post-heading phenology differences is consistent with the experimental results of Idso (1982) and Hatfield et al. (1984).

The vapor pressure deficit at which the canopy-air temperature differential initially departed from the "non-water-stressed" baseline (3-h smoothing) for each irrigation treatment is shown in Fig. 5 in relation to the estimated 1.6-m profile available water on the same date. This relationship is likely "site-specific," but it illustrates the effect of evaporative demand on the transpiration from wheat, like that shown by Idso et al., (1982) for cotton, Fig. 5 indicates a slope approximately 64% larger than Idso et al. (1982) reported for cotton at Phoenix, AZ, which reflects both crop species and soil property differences. The major difference would be crop species related since wheat would be expected to be adapted to a cooler environment than cotton.

The canopy-air temperature differential for the water-stressed treatment (T-1) of TAM-105 is shown in Figs. 6

TABLE 1. NON-WATER-STRESSED BASELINES DETERMINED BY LINEAR REGRESSION FROM MEASUREMENTS TAKEN ON MAY 3 AND 21 ON THE FULL IRRIGATION TREATMENTS

Smoothing technique	Variety	a*	b	r^2	$S_{y/x}$	S_a	S_b
May 3, 1984 (Pre-heading)							
Plot mean N = 24	TAM-105	0.925	+1.976	0.914	0.396	0.129	0.230
	TAM-108	0.496	+1.640	0.751	0.617	0.201	0.358
	Sturdy	1.125	+1.843	0.925	0.343	0.112	0.199
	Scout	0.840	+1.812	0.859	0.481	0.157	0.280
Treatment mean N = 8	TAM-105	0.929	+1.978	0.956	0.307	0.173	0.309
	TAM-108	0.497	+1.639	0.912	0.368	0.208	0.370
	Sturdy	1.126	+1.844	0.966	0.252	0.142	0.253
	Scout	0.842	+1.813	0.952	0.293	0.165	0.295
3-hour running mean N = 6	TAM-105	1.083	+2.087	0.980	0.167	0.151	0.260
	TAM-108	0.467	+1.624	0.968	0.164	0.148	0.255
	Sturdy	1.069	+1.820	0.985	0.125	0.113	0.195
	Scout	1.050	+1.926	0.993	0.090	0.081	0.140
May 21, 1984 (Post-heading)							
Plot mean N = 24	TAM-105	1.630	+1.333	0.827	0.503	0.130	0.397
	TAM-108	1.257	+1.186	0.869	0.380	0.098	0.300
	Sturdy	1.959	+1.405	0.927	0.326	0.084	0.257
	Scout	1.753	+1.246	0.846	0.439	0.113	0.346
Treatment mean N = 8	TAM-105	1.631	+1.333	0.963	0.240	0.107	0.328
	TAM-108	1.259	+1.186	0.953	0.240	0.107	0.327
	Sturdy	1.962	+1.406	0.982	0.174	0.078	0.237
	Scout	1.529	+1.180	0.944	0.263	0.118	0.360
3-hour running mean N = 6	TAM-105	1.541	+1.290	0.998	0.044	0.031	0.093
	TAM-108	1.065	+1.103	0.985	0.097	0.068	0.207
	Sturdy	1.998	+1.410	0.994	0.078	0.055	0.167
	Scout	1.359	+1.107	0.996	0.048	0.034	0.103

*a = intercept, b = slope, r^2 = coefficient of determination, $S_{y/x}$ = standard error of estimate of y on x, S_a = standard error of regression intercept, and S_b = standard error of regression slope for the regression equation Y = a - bX, with Y in units of C and X in units of kPa.

and 7 for the pre- and post-heading conditions, respectively. Shown in these figures is the non-transpiring (water-stressed) canopy-air temperature differential estimated by the procedure of Idso et al. (1981a) as described earlier. In general, the estimated stressed (non-transpiring) baseline was in good agreement with the measured T_c - T_a from treatment T-1 of approximately 1 to 3°C. The predicted upper baselines for TAM-105 based solely on the previously determined " non-water-stressed" baselines were T_c -T_a = 0.96 + 0.0236 T_a and T_c - T_a = 1.44 + 0.020 T_a for pre-and post-heading, respectively. No strong correlation existed between T_c - T_a and 2-m windspeed (30-min average) (r = 0.24) in the stressed treatment (T-1); however, the measured windspeeds were generally larger (ranging from 1.5 to 9.8 m s^{-1}) than those reported by

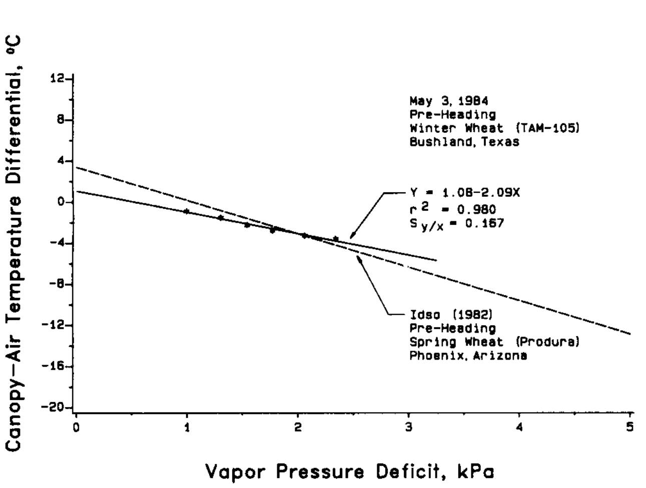

Fig. 3—Non-water-stressed baseline for TAM-105 winter wheat during pre-heading using 3-h running mean smoothing technique for treatment T-4.

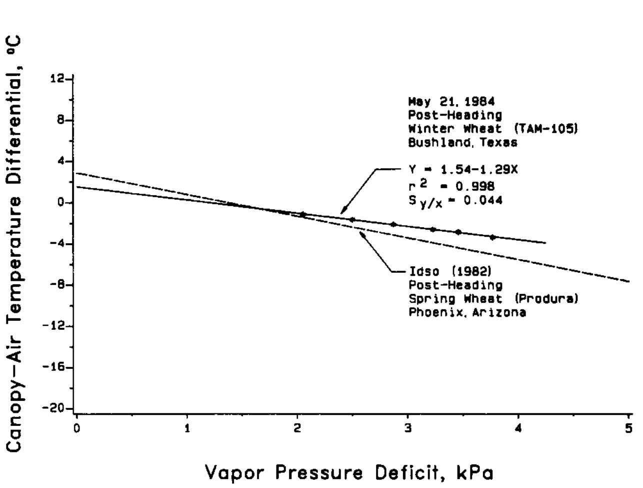

Fig. 4—Non-water-stressed baseline for TAM-105 winter wheat during post-heading using 3-h running mean smoothing technique for treatment T-4.

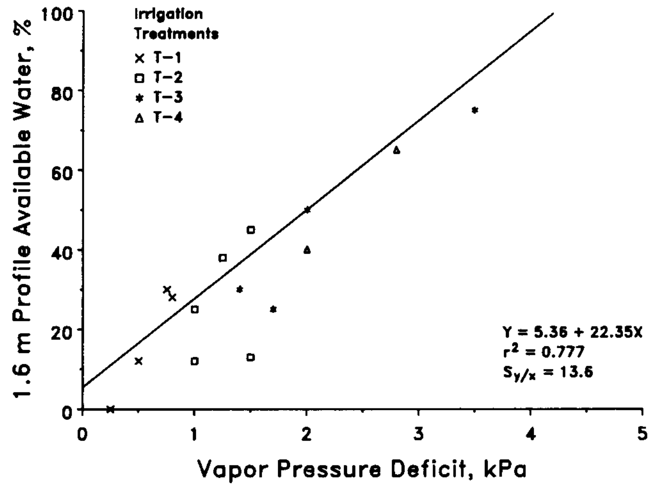

Fig. 5—The vapor pressure deficit at which crop water stress develops in relation to the amount of profile soil water remaining at the same time.

TABLE 2. ESTIMATED CANOPY AERODYNAMIC AND DIFFUSION RESISTANCES, s m^{-1}, AT 600 W m^{-2} OF NET RADIATION AND MEAN TEMPERATURE CONDITIONS

Parameters*	Varieties TAM-105	TAM-108	Sturdy	Scout
Pre-Heading				
r_{aU}	2.7	1.1	2.6	2.5
r_{aL}	3.0	1.2	2.8	2.8
r_{cL}	10.5	7.1	14.1	12.8
Post-Heading				
r_{aU}	3.4	2.3	4.5	2.9
r_{aL}	3.7	2.3	4.7	3.0
r_{cL}	30.5	30.8	36.0	32.2

*r_{aU} = aerodynamic resistance determined from equation [9], r_{aL} = aerodynamic resistance determined by equation [4] and equation [5], and r_{cL} = canopy diffusion resistance determined by equation [4] and equation [5] (see Idso (1983) and O'Toole and Real (1986) for procedural details).

O'Toole and Hatfield (1983), which ranged from 0.4 to 3.2 m s^{-1}. Increased windspeed should decrease the sensitivity of T_c - T_a to windspeed since r_a should approach an asymptotic lower value. It should be noted that the field measurements should be indicative of stress levels less than maximum, particularly before heading,

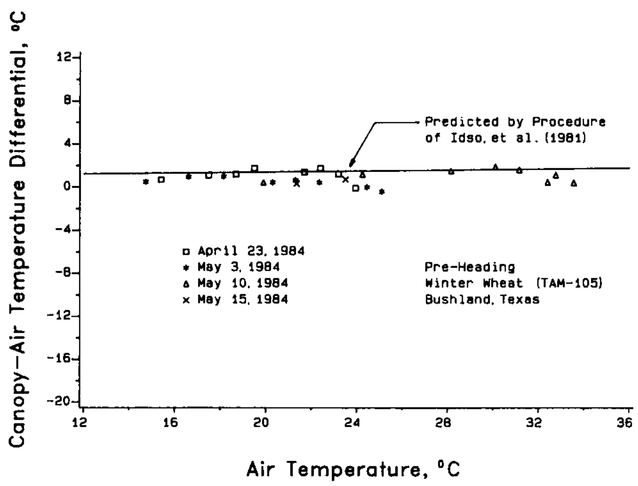

Fig. 6—Non-transpiring baselines for TAM-105 winter wheat for pre-heading for treatment T-1.

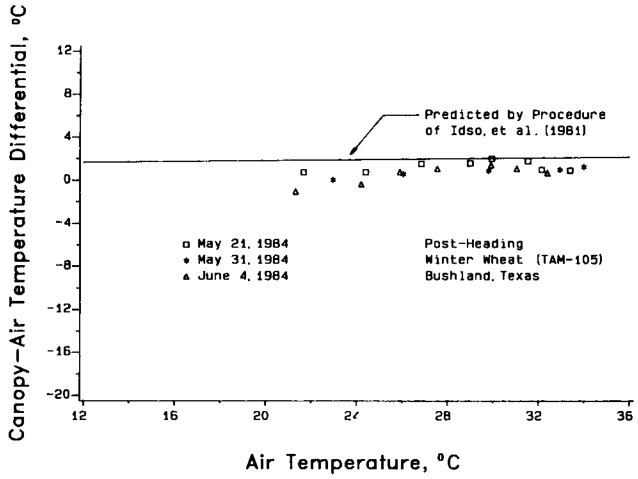

Fig. 7—Non-transpiring baselines for TAM-105 winter wheat for post-heading for treatment T-1.

since transpiration was still occurring (Fig. 2), although at a reduced rate.

Table 2 presents the computed aerodynamic and canopy diffusion resistances estimated from the baseline information. The r_{aU} was computed using equation [9] and the mean T_a to estimate T_c - T_a for the non-transpiring case. The r_{aL} was computed using the relation between equations [4] and [5]. All computations used a R_n value of 600 W m^{-2} simply for comparison purposes and ρ C_p was determined based on mean temperature and barometric pressure conditions for Bushland. A rather striking similarity was apparent in two estimated values of r_a for each variety. Although the two procedures for estimating r_a were not totally independent, it is somewhat encouraging that the two methods agreed. The varietal differences in r_a, however, may not be of any significance. The values of r_a remained relatively stable from pre- to post-heading, while the estimated r_c values indicated a large increase from pre- to post-heading as is normally found in field and laboratory studies of leaf diffusion resistance (Frank et al., 1973). The pre-heading values are qualitatively similar to the vegetative values for rice reported by O'Toole and Real (1986) using a similar technique. Hatfield (1985) reported a canopy diffusion resistance—solar radiation relationship for spring wheat (Anza) which would predict a r_c of 27.0 s m^{-1} at 800 W m^{-2} of solar radiation (approximately similar to 600 W m^{-2} of net radiation). This compares rather well with the post-heading predicted values, which ranged from 30.5 to 36.0 s m^{-1} for these winter wheat varieties.

The CWSI was estimated using the Idso et al. (1981a) procedure as presented in equation [7] for each of the days of diurnal measurements. The corresponding leaf water potential (LWP) value was correlated to the CWSI; however, the relationship depended on the pre- or post-heading phenology. The relationships are shown in Figs. 8 and 9, respectively. The pre-heading relationships between LWP and CWSI had a coefficient of determination of 0.42, and the standard error of the estimate of y on x was 0.51 MPa. The post-heading relationship had an improved coefficient of determination of 0.85 and a reduced standard error of the estimate of y on x of 0.37 MPa. The relationships were not tested for varietal commonality, but graphical

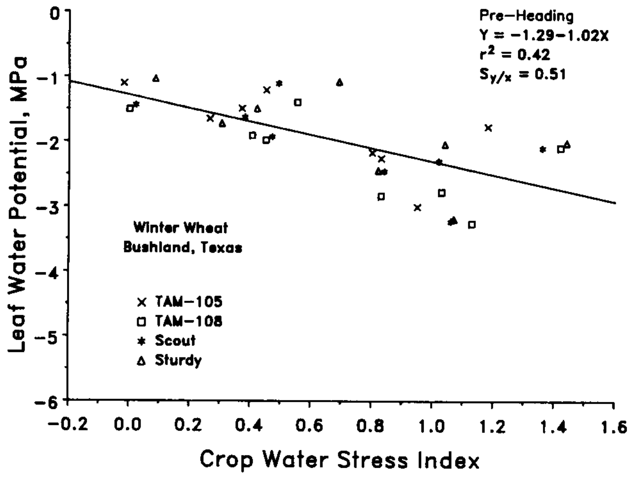

Fig. 8—Relationship between the crop water stress index determined by infrared thermometry and leaf water potential as influenced by pre-heading in four winter wheat varieties.

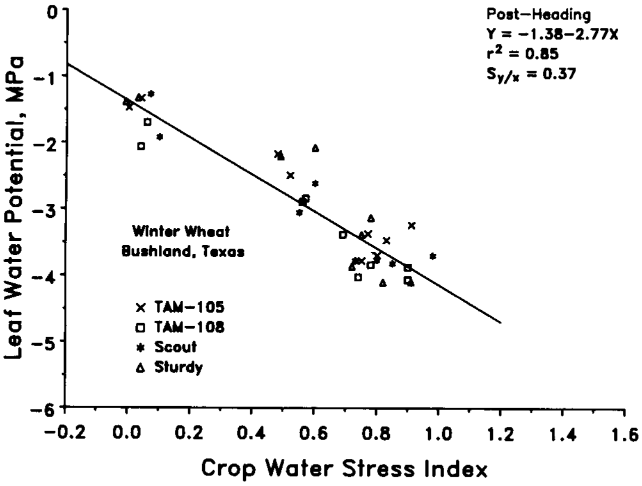

Fig. 9—Relationship between the crop water stress index determined by infrared thermometry and leaf water potential as influenced by post-heading in four winter varieties.

inspection does not indicate any major varietal effects on the relationships. The difference between the two relationships, between pre- and post-heading, may have resulted from sampling only the flag leaves for LWP after heading. The flag leaves are more exposed to the environment than the canopy leaves, and previous studies (Frank et al., 1973) have noted that the flag leaf appears to have different water relations than lower canopy leaves. However, there was not a large effect of pre- and post-heading on the "non-water-stressed" LWP as exhibited by the relationships at zero CWSI.

Since the LWP measurements were made only at one time of day, we did not have great enough range in VPD to establish the function between VPD and LWP for these winter wheats. Therefore, the "soil-induced" LWP (Idso et al., 1981b) could not be determined.

SUMMARY

An experiment conducted at the USDA-ARS, Conservation and Production Research Laboratory in the Southern Great Plains studied the canopy temperature of several winter wheat varieties under four soil water regimes controlled by irrigation. The four winter wheat varieties—TAM-105, TAM-108, Sturdy, and Scout—were found to produce different "non-water-stressed" lower baselines, depending on the method of data smoothing and on the phenology change from pre- to post-heading. The data smoothing techniques were not significantly different. The "non-transpiring" upper baseline was estimated accurately using the procedure of Idso et al. (1981a) and no apparent windspeed effect was noted with the wind conditions common to this region. If very calm conditions (windspeeds less than 1.5 m s $^{-1}$) occur, an increase in canopy temperature under water stress as reported by O'Toole and Hatfield (1983) would be expected to occur.

The "non-water-stressed" and "non-transpiring" baselines predicted consistent aerodynamic resistance between varieties and for pre- and post-heading phenology. However, large differences were predicted using the "non-water-stressed" baselines for the canopy diffusion resistance from pre- and post-heading.

The CWSI was found to be related to LWP as measured by thermocouple psychrometry. The relationship, however, depended on phenology (pre- and post-heading), although this effect may simply be due to the difference in water relations of the flag leaves and canopy leaves in wheat.

The CWSI could be expected to be a reliable tool for timing spring irrigations for winter wheat. However, irrigation scheduling requires decisions about both timing and amount. The profile soil water content at which wheat water stress develops in this soil was shown to be influenced by the evaporative demand. This relationship can now be used to estimate the timing of wheat irrigations to minimize crop water stress. The CWSI would appear to a useful supplement to traditional irrigation scheduling models (Jensen et al., 1971) as a means to determine more precisely when to irrigate while the soil water balance can be used to predict the irrigation amount.

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